KFKI-1980-57

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BUDAPEST

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HU ISSN 0368 5330
ISBN 963 371 688 8

ABSTRACT

The possibility exists to design a measuring device for comparing spectra; the device works on the analogy of colour vision. Furthermore, the use of this device enables changes /in a machine's condition/ to be detected.

АННОТАЦИЯ

Имеется возможность создания измерительного прибора, способного осуществлять сравнение спектров по аналогии с механизмом цветового восприятия человеческим глазом. Прибор в ограниченной степени может быть применен дла вибрационно-диагностического контроля механических конструкций оборудовании.

KIVONAT

Az emberi szem szinlátásmechanizmusának analógiájára épithető olyan mérőegység, amely lehetőséget biztosit spektrumok összehasonlitására. Az igy kialakitott eszköz korlátozott mértékben alkalmasnak látszik gépészeti berendezések állapotának vibrációdiagnosztikai ellenőrzésére.

INTRODUCTION

Investigations into vibration-diagnostics of mechanical structures, engines and mechanisms have shown a rapid increase of late. The detection of irregularities and the determination of faults are the vital goals of such investigations. In most cases, but above all in the case of essential and expensive mechanisms, permanent control is of paramount importance. For more than one specific component, it is generally not sufficient to determine the anomaly but it is also necessary to point out the origin of the fault. One way to solve the problem is to watch the characteristic spectrum-bands or to observe the sources of the noise or the vibration. The former of these makes use of filters or a frequency-analyser, the latter a series of sensors. In practice, plausible results are generally attainable by the mixed instrumentation of both of the mentioned methods.

In this paper a new method, at present in the experimental phase is discussed in order to design an inexpensive and simple instrument which has a limited ability for spectrum comparison and for the detection of a machine's condition. Previously those possibilities were studied that allowed the observation of more numerous spectral-bands than the utilized filters. If the relationship of the effective values of filtered signals is considered as information, the use of overlapped filters looks promising. One of the simplest accomplishments is realizable by two or three overlapped filters. Theoretically, this is identical with the mechanism of colour vision. Naturally the filters in limited numbers cause the restriction of information.

THE MECHANISM OF COLOUR VISION AND THE CONFORM SIGNAL IDENTIFIER

Human beings and certain other living organisms possess a visual mechanism which enables them to attach a definite sense - by name, colour - to the visible range of the electromagnetic field. Colour vision depends on three types of cone cell, each of which contains one of three visual pigments. Young's idea that colour results from the independent excitation of three kinds of cone lends itself to a three-vector graphical representation or to the colour triangle.

It is possible to design a measuring device on the analogy of the known phenomenon which connects a measure, such as colour, in a colour triangle to noises or vibrations.

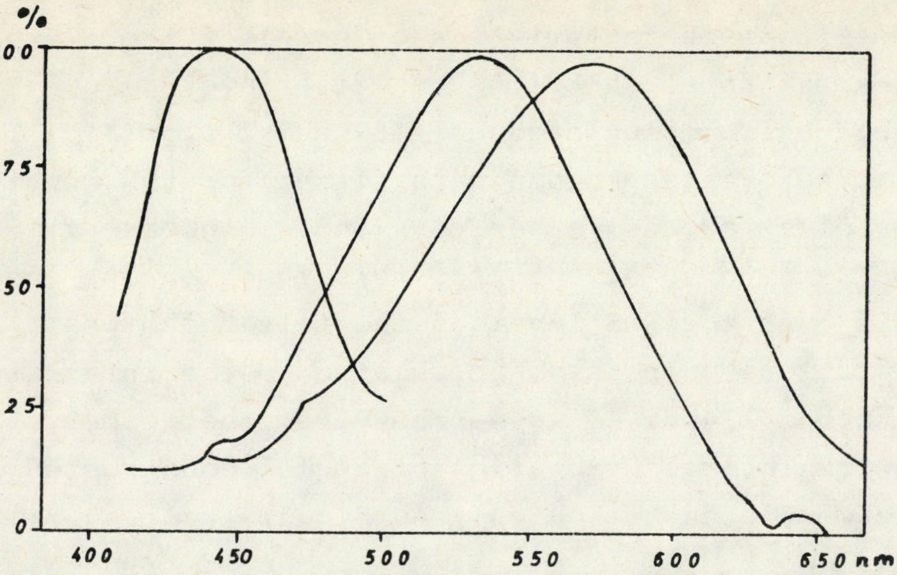

Fig. 1

Three cone pigments of normal colour vision absorb lights of different wavelengths as plotted here. The curves are the average spectral absorbance from single cones in excited eyes of humans scaled to the same maximas. /F. MacNichols Jr.; 1964 Johns Hopkins Univ./

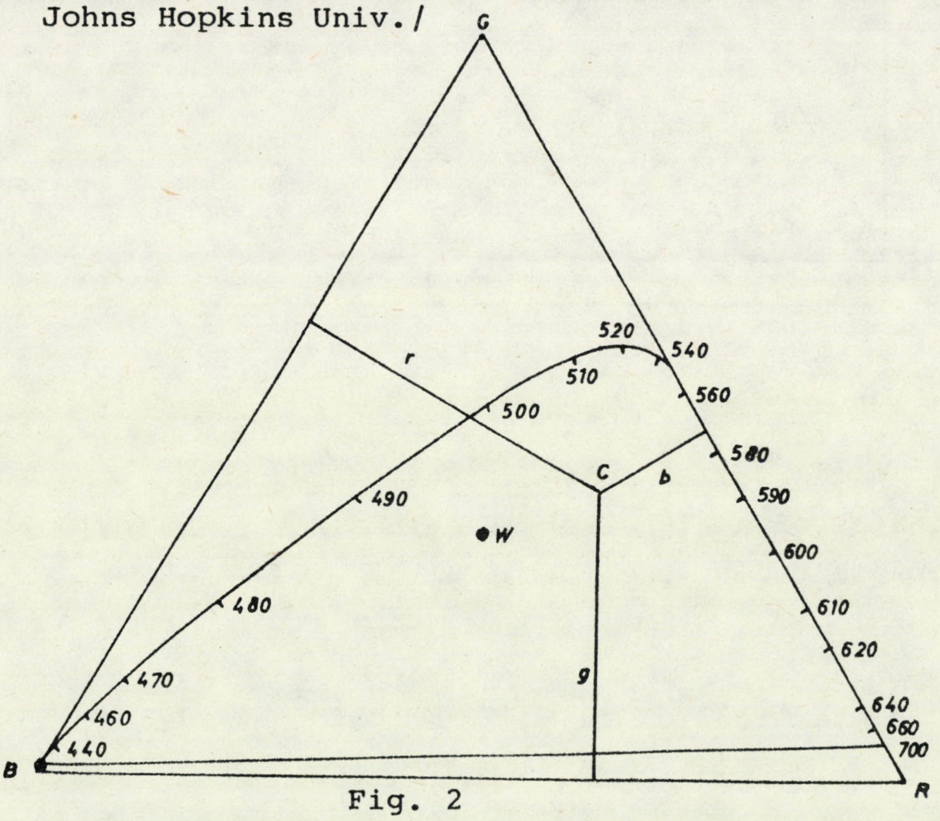

Fig. 2

Colour triangle - one of many possible. The lengths of r,g,b, perpendicular to C, correspond the the absorbed light of each of the three types of cones. The curve shows the position of various beams of monochromatic light, the point W represents the white light.

The amplitude-characteristics of single filters are the nearest approach to the curves of average spectral absorbance from single cones. It seems, from Fig. 1, that three overlapped bandpass filters or the combination of a lowpass, a bandpass and a highpass filter can be used to substitute for this function of cones. In this case the RMS level of the filtered signals of vibrations or noises are related to the intensity of absorbed light. If we set out from the geometry of an equilateral "vibration triangle" constructed on the mentioned analogies /see Fig.3/

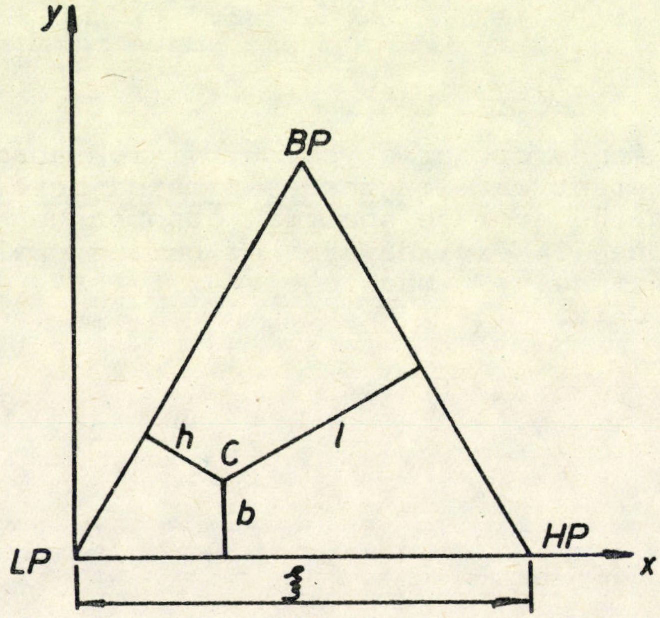

Fig. 3

we obtain the following equations where the coordinates of a signal or spectrum in the triangle are represented by the point C:

$$C_x = (b + h \sin 30^\circ)\ \mathrm{ctg}\,60^\circ + h \cos 30^\circ \qquad /1/$$
$$C_y = b$$

Since the quantities b,h,l are proportional to the effective values of the filtered signal,

$$l = a\,L$$
$$b = a\,B \qquad /2/$$
$$h = a\,H$$

where L,H,B are the RMS values of filtered signal produced by a lowpass, a bandpass and a highpass filter or three bandpass filters with different central frequencies.

The transformational or compresional constant is

$$a = \frac{\xi \sin 60^{\circ}}{L + B + H} \qquad /3/$$

where ξ is the lengths of a side of an equilatered triangle /enlarged for purposes of illustration/.

Thus, the coordinates of the spectrum or signal are

$$C_x = \frac{0.5B + H}{L + B + H}\,\xi$$
$$/4/$$
$$C_y = \frac{0.866B}{L + B + H}\,\xi$$

Similar results can be obtained for other triangles.

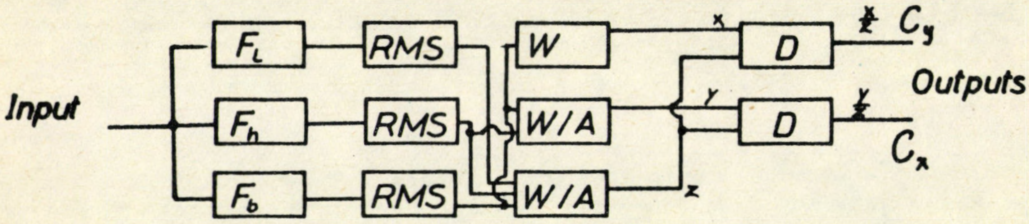

Fig. 4
Principle of operation of instrumentation used for "vibration triangle" realization.

F_l - lowpass filter
F_b - bandpass filter
F_h - highpass filter
D - analogue divider
W - weighting circuit
W/A - weighting and adding circuit
RMS - root mean square circuit

THEORETICAL CHARACTERISTICS OF THE INSTRUMENT AND LIMITS OF UTILIZATION

It is easy to see that the instrument can be used only in those frequency-ranges where at least two filters produce valuable signals. The obtained results are disturbed by other frequencies. Thus the interpreted frequency-ranges are limited. The exact measurments need the elimination of the outer frequency components. A bandpass filter ensures this task. But this does not automatically mean the enhancement of the number of filters. Because a bandpass filter of one of three with increased bandwidth is suitable for this purpose. In this case it is not the ratio of the three filtered signals that appear in the triangle but the original and two filtered signals. This is not a new finding and the presented information is identical with the previous knowledge.

Equation 4 shows that the triangle cannot give information for the RMS value of signal or for the intensity of vibration.

A question of fundamental importance concerns which of the spectras have the same coordinates in the triangle. For this reason it is worth while writing some expressions in detailed form.

Let f/t/ be the observed signal and F/j ω / its Fourier transform pair or spectrum. Supposing that the signal is periodical with T periodicity and F/j ω / components only in the range between ω=0 and $\omega = \omega_m$ then the well-known equation

$$\int_{-\infty}^{\infty} f^2/t/\ dt = \frac{1}{2\pi} \int_{-\infty}^{\infty} F/j\omega/^2\ d\omega \qquad /5/$$

would be transformed to the form

$$\int_{0}^{T} f^2/t/\ dt = \frac{1}{2\pi} \int_{0}^{\omega_m} F/j\omega/^2\ d\omega \qquad /6/$$

The left side of Eq. 6. is proportional to the RMS value of the signal or to the intensity. Let $H_1/j\omega/$, $H_2/j\omega/$,$H_3/j\omega/$ be the comlex transfer functions of filters. If we substitute in Eq. 6., it leads to

$$\int_{0}^{T} f_n^2/t/\ dt = \frac{1}{2\pi} \int_{0}^{\omega_m} /F/j\omega/\ H_n/j\omega//^2\ d\omega \qquad /7/$$

n=1,2,3

Let us suppose another spectrum, $F^{*}/j\omega/$, which differs from $F/j\omega/$ but has the same limits. The signals or spectras produce equal coordinates in the triange, if

$$\int_{0}^{\omega_m} /F^{*}/j\omega/H_n/j\omega//^2\, d\omega = C\int_{0}^{\omega_m} /F/j\omega/H_n/j\omega//^2\, d\omega \qquad /8/$$

$n=1,2,3$

The constant C is determined by the effective values of nonfiltered signals.

The equations 5,6,7 and 8 are not under influence of phases. Thus the "vibration triangle" cannot present information for these. It is sufficient to take into consideration only the amplitude-spectras and the transfer functions of filters. Henceforth $f/\omega/$ and $f^{*}/\omega/$ are the amplitude-spectras and $h_1/\omega/, h_2/\omega/, h_3/\omega/$ are the transfer characteristics of filters. Substituting these functions into Eq. 8. and writing it an simplified alternative form, then we obtain

$$\int_{0}^{\omega_m} /f/\omega/h_n/\omega//^2\, d\omega = C\int_{0}^{\omega_m} /f^{*}/\omega/h_n/\omega//^2\, d\omega \qquad /9/$$

or

$$\int_{0}^{\omega_m} /f/\omega/^2 - C\, f^{*}/\omega/^2/\, h_n^2/\omega/\, d\omega = 0 \qquad /10/$$

$n=1,2,3$

Let

$$/f/\omega/^2 - C\, f^{*}/\omega/^2/\; h_2^2/\omega/ = f_2^2/\omega/ \qquad /11/$$

If the integral of $f_2^2/\omega/$ on $0-\omega_m$ with respect to ω and following equations are valid, the signal produces equal coordinates in the triangle.

$$\int_0^{\omega_m} f_2^2/\omega/\; \frac{h_1^2/\omega/}{h_2^2/\omega/}\, d\omega = 0 \qquad \int_0^{\omega_m} f_2^2/\omega/\; \frac{h_3^2/\omega/}{h_2^2/\omega/}\, d\omega = 0 \qquad /12/$$

The used form in Eq. 12. makes easier the analysis just like the series form of Eq. 11. and 12. If we consider limited periodic functions which are identical with the difference of power-spectras during the interval $0 - \omega_m$ and have a period ω_m and if we then apply the Fourier transformation to these, then useful forms appear, viz.

$$f_2^2/\omega/ = \sum_{n=1}^{\infty} a_n \cos n\frac{2\pi\omega}{\omega_m} + b_n \sin n\frac{2\pi\omega}{\omega_m}$$

$$\frac{h_1^2/\omega/}{h_2^2/\omega/} = \frac{a_o^{12}}{2} + \sum_{n=1}^{\infty} a_n^{12} \cos n\frac{2\pi\omega}{\omega_m} + b_n^{12} \sin n\frac{2\pi\omega}{\omega_m} \qquad /13/$$

$$\frac{h_3^2/\omega/}{h_2^2/\omega/} = \frac{a_o^{32}}{2} + \sum_{n=1}^{\infty} a_n^{32} \cos n\frac{2\pi\omega}{\omega_m} + b_n^{32} \sin n\frac{2\pi\omega}{\omega_m}$$

$$a_o = 0 \text{ because } \int_0^{\omega_m} f_2^2/\omega/\, d\omega = 0$$

Substituting Eq. 13. into Eq. 12.

$$\int_0^{\omega_m} \sum_{n=1}^{\infty} a_n\, a_n^{12} \cos^2 n \frac{2\pi\omega}{\omega_m} + b_n\, b_n^{12} \sin^2 n \frac{2\pi\omega}{\omega_m} \; d\omega = 0$$
$$\int_0^{\omega_m} \sum_{n=1}^{\infty} a_n\, a_n^{32} \cos^2 n \frac{2\pi\omega}{\omega_m} + b_n\, b_n^{32} \sin^2 n \frac{2\pi\omega}{\omega_m} \; d\omega = 0 \qquad /14/$$

Equation 14 is satisfied by the infinite variations of the values of a_n, a_n^{12}, a_n^{32}, b_n, b_n^{12}, b_n^{32}. Thus a point in the triangle represents innumerable spectras. But some practical limitations need to be taken into consideration, thus for the constants of Eq. 14.

$$a_n,\ b_n \in \left[-K_1, K_1\right]$$
$$a_n^{12},\ a_n^{32},\ b_n^{12},\ b_n^{32} \in \left[-K_2, K_2\right] \qquad /15/$$

where K_1 and K_2 are positive constants.

The filters should be chosen so that the functions $h_1^2/\omega/\ /h_2^2/\omega/$ and $h_3^2/\omega/\ /h_2^2/\omega/$ are monotonous on $0 - \omega_m$. This case is derived automatically from the usage of a lowpass, a bandpass and a highpass filter, where the bandpass filter is used for the elimination of undesired frequency components. / The transfer characteristic of bandpass filter is approximately constant./ Under this condition the series of absolute values of a_n^{12}, a_n^{32}, b_n^{12} and b_n^{32} with respect to n decrease monotonously.

Considering that in practice the signals or spectras have stochastical properties, then if Eq. 16. is valid

$$ABS\,(f/\omega/ - f^{*}/\omega/) \leq \Delta f \qquad /16/$$

where Δf is an arbitrary small constant

then the spectras $f/\omega/$ and $f^{*}/\omega/$ are equal. Hence the sufficient conditions for the identity is

$$\left| \int_{o}^{\omega_m} f_2^2/\omega/\, d\omega \right| = \left| \frac{a_o}{2} \right| \leq \Delta e_2 \qquad /17/$$

$$\left| \int_{o}^{\omega_m} \frac{a_o\, a_o^{12}}{4} + \left(\sum_{n=1}^{\infty} a_n\, a_n^{12} \cos^2 n \frac{2\pi\omega}{\omega_m} + b_n\, b_n^{12} \sin^2 n \frac{2\pi\omega}{\omega_m} \right) d\omega \right| \leq \Delta e_1$$

$$\left| \int_{o}^{\omega_m} \frac{a_o\, a_o^{32}}{4} + \left(\sum_{n=1}^{\infty} a_n\, a_n^{32} \cos^2 n \frac{2\pi\omega}{\omega_m} + b_n\, b_n^{32} \sin^2 n \frac{2\pi\omega}{\omega_m} \right) d\omega \right| \leq \Delta e_3$$

where Δe_1, Δe_2, Δe_3 are arbitrary small constants

Using the introduced limitations for a_n^{12}, a_n^{32}, b_n^{12}, b_n^{32} the following equations are evident:

$$\left| \int_{0}^{\omega_m} \sum_{n=N+1}^{\infty} a_n\, a_n^{12} \cos^2 n\frac{2\pi\omega}{\omega_m} + b_n\, b_n^{12} \sin^2 n\frac{2\pi\omega}{\omega_m} \; d\omega \right| \ll \Delta e_1$$

/18/

$$\left| \int_{0}^{\omega_m} \sum_{n=N+1}^{\infty} a_n\, a_n^{32} \cos^2 n\frac{2\pi\omega}{\omega_m} + b_n\, b_n^{32} \sin^2 n\frac{2\pi\omega}{\omega_m} \; d\omega \right| \ll \Delta e_3$$

Thus, equations /17/ could be approximated as

/19/

$$\left| \int_{0}^{\omega_m} \frac{a_o\, a_o^{12}}{4} + \left(\sum_{n=1}^{N} a_n\, a_n^{12} \cos^2 n\frac{2\pi\omega}{\omega_m} + b_n\, b_n^{12} \sin^2 n\frac{2\pi\omega}{\omega_m} \right) d\omega \right| \leq \Delta e_1$$

$$\left| \int_{0}^{\omega_m} \frac{a_o\, a_o^{32}}{4} + \left(\sum_{n=1}^{N} a_n\, a_n^{32} \cos^2 n\frac{2\pi\omega}{\omega_m} + b_n\, b_n^{32} \sin^2 n\frac{2\pi\omega}{\omega_m} \right) d\omega \right| \leq \Delta e_3$$

The numerical value of N is determined by the filters and the compared signals. Since the constants in Eq. 19. are limited these would be divided into a large number of small and equal parts. Theoretically the power-spectras, which are represented by the same point or coordinates in the triangle, can be determined from the variations of possible magnitudes graded by the divisions. Of course a point in the triangle represents a large number of spectra but as was to be expected three filters cannot reproduce the signals or spectras.

The device makes a unidirectional signal transformation. The transformation is irreversible.

If we set out from the primary function of the method mentioned in the introduction then it is sufficient to detect the difference between the spectra of normal and abnormal conditions. It is not difficult to differentiate between the RMS levels of filtered signals by this method. Only substracting components are needed between the RMS and weighting circuits /see Fig. 4/ but one must make sure that the differences are of the same sign. If the signal of the machine's condition is normal then the device cannot present definite result, the system is undetermined. If the abberation is limited to a small spectral range the identification point will be positioned near the boundary curve, indicating exactly the frequency of irregularities.

MEASURING DEVICE FOR EXPERIMENTAL PURPOSES

For researching the applicability of a "vibration triangle" a measuring device is realized with the simplest circuits possible. The charasteristics of filters are chosen so that the frequency range of triangle spans the noise or vibration spectra of rotating machines.

Specifications:

frequency range: 100 - 5000 Hz

filters:

- first-order lowpass: f_c = 500 Hz
- first-order highpass: f_c =3000 Hz
- bandpass: f_b =1000 Hz Q=0.5

f_c - critical frequency
f_b - resonance frequency

The theoretical characteristics of single filters are shown in Fig. 5., Fig. 6. represents the triangle originating from them.

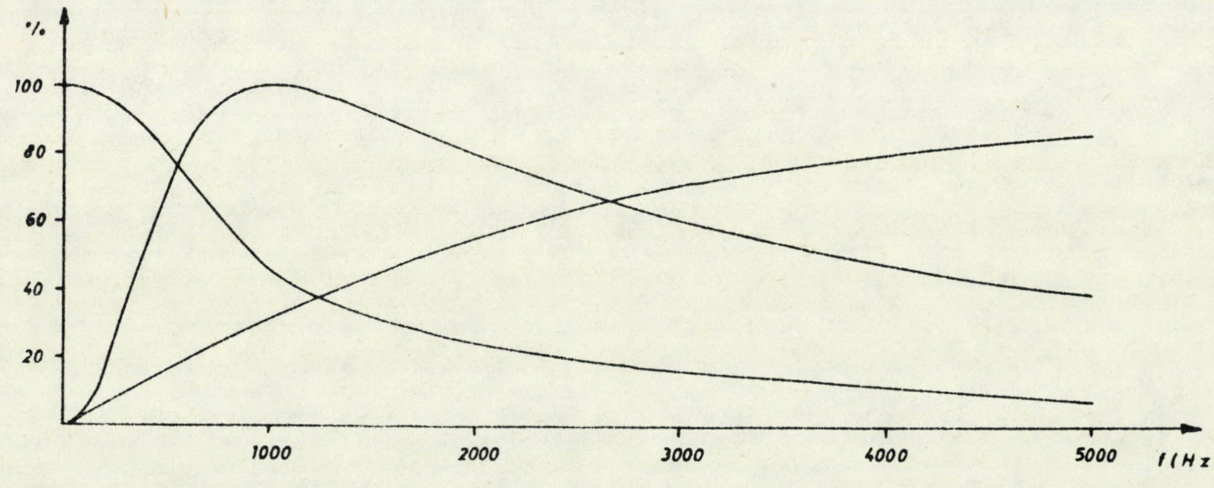

Fig. 5

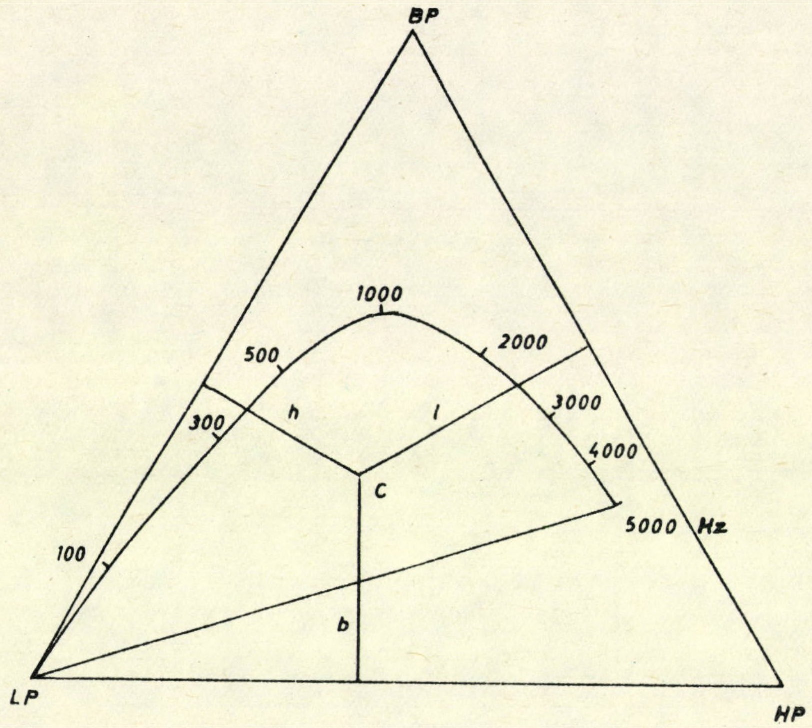

Fig. 6

By using the realized measuring device the boundary-curve /sine input/ and some identification points of different spectras are shown in Fig. 7. The points represent two different spectras which are modified by the standard A,B,C and D filters. The nonfiltered spectras, indexed with "L" in fig.7., are shown in Fig. 8. and Fig. 9. The spectrum components under 100 Hz and above 5000 Hz were eliminated. Figure 7 shows that the identical filtering of the two spectras cause similar movements in the triangle. Thus the direction of movements refers, within limited bands, to the variation of spectra.

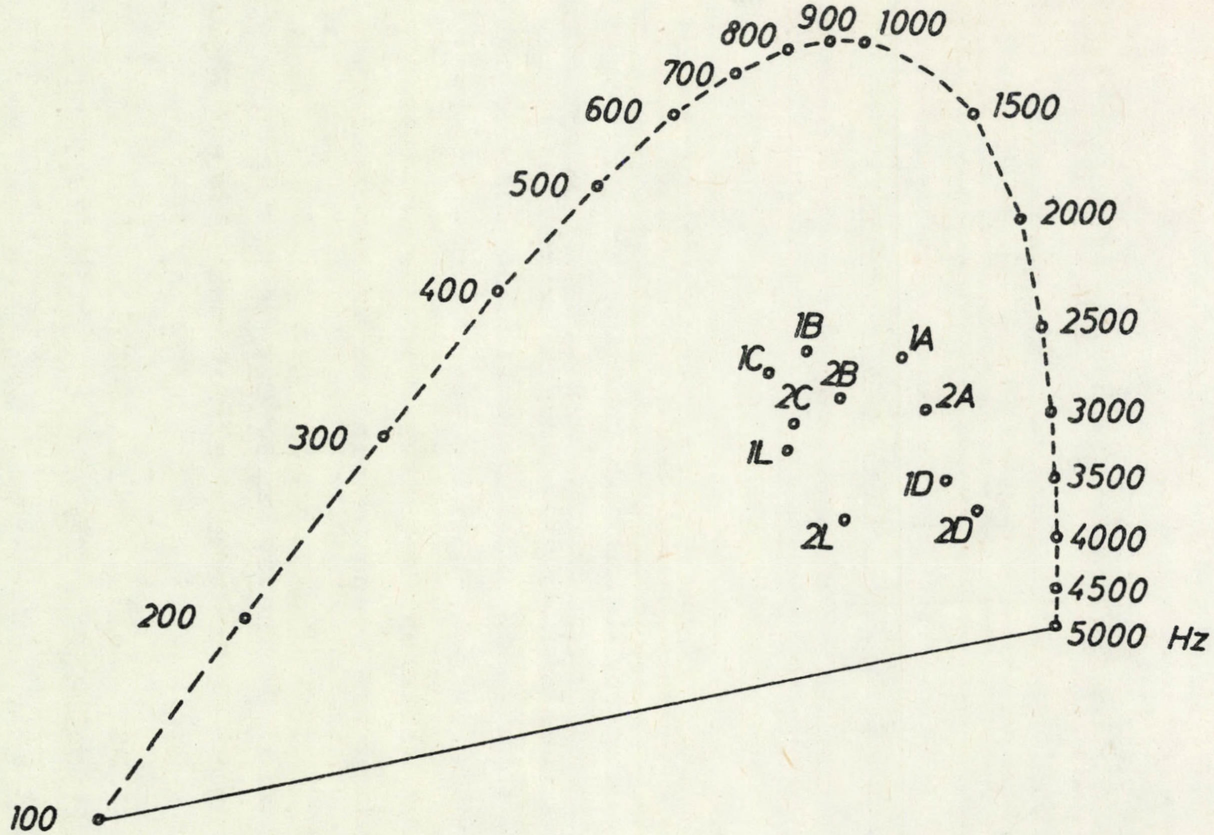

Fig. 7

Boundary-curve and some identification points of spectras produced by the realised measuring device.

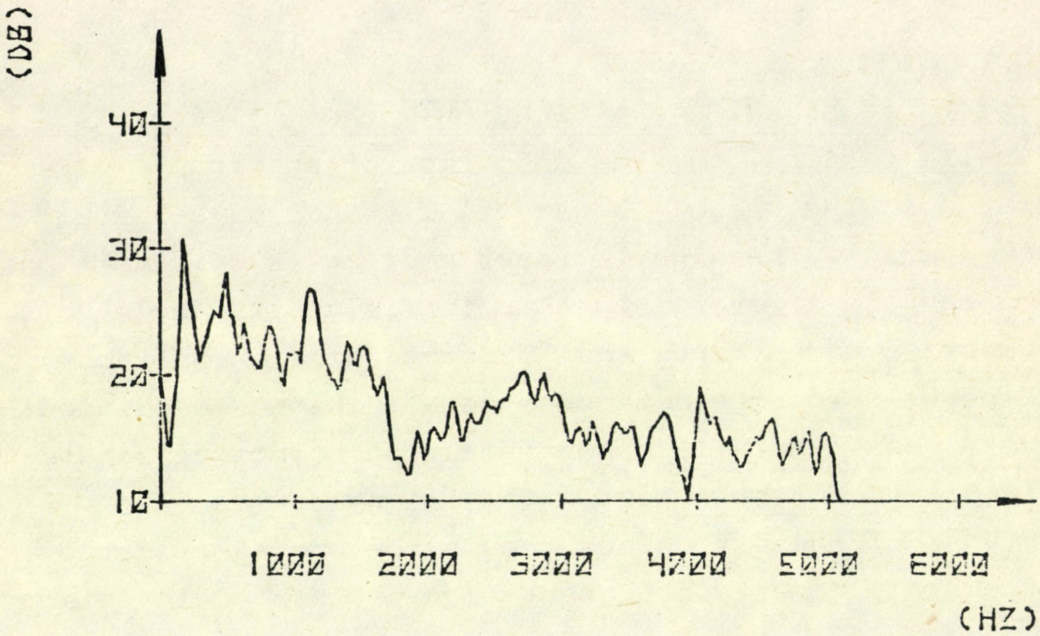

Fig. 8

Power spectrum of signal "1L"

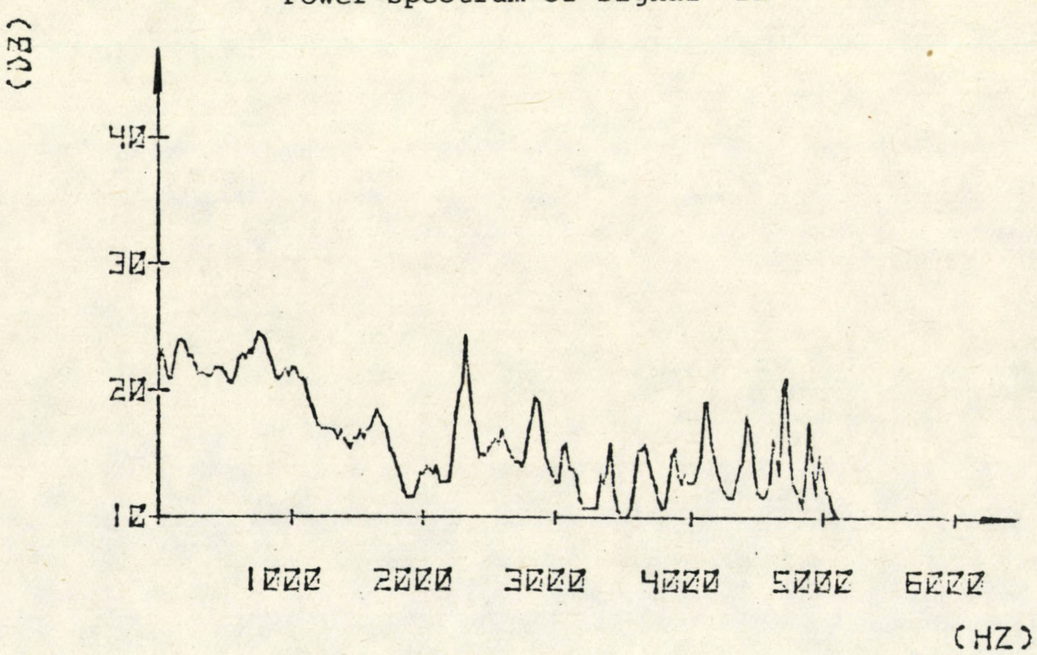

Fig. 9

Power spectrum of signal "2L"

SUMMARY:

The described signal identification method is suitable, within limitations, for the detection of spectral alterations. The method is essentially that of a large data reduction. The signal transformation is unidirectional, unambiuous and irreversible. A point in the triangle represents numerous spectras. Theoretically the method could be used for the detection of a machine's condition in every case where the identification points of single conditions do not coincide in the triangle. The main advantages of the method and the device are simplicity and the small amount instrumentation necessary. In this method the three overlapped filters can produce more information than three but a finite numbers of filters. The practicability of the method can be determined only in practice; research work with this in mind is currently being carried out.

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IEEE vol. AU-20, no.1 March 1972

63.071

Kiadja a Központi Fizikai Kutató Intézet
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Budapest, 1980. augusztus hó